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Mantle lateral variations and elastogravitational deformations – II. Possible effects of a superplume on body tides

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SUMMARY

The body tides response (deformation and gravity) of the Earth is generally computed assuming radial symmetry in stratified earth models, at the hydrostatic equilibrium. We present in this paper numerical experiments with the aim to evaluate the impact of very large mantle heterogeneities of density on body tides.

In a companion paper, we have developed a new earth elasto-gravitational deformation model able to take into account the heterogeneous structure of the mantle. We use this model to calculate the theoretical perturbation induced by three types of spherical heterogeneities in the mantle on M2 body tides response. The heterogeneities are: (1) our limit case, a heterogeneity of 1000 km of radius in the lower mantle; (2) a heterogeneity of 500 km of radius at the bottom of the lower mantle and (3) a heterogeneity of 285 km of radius in the upper mantle. The density variation has been set to -50 kg m^{-3}. For each experiment, we first calculate the equilibrium state of the Earth when it contains a heterogeneity, including non-hydrostatic pre-stresses, dynamical topography and lateral variation of density. Then we compute the M2 tidal perturbation. We find that the surface tidal displacement perturbation is smaller than 1 mm, and that the gravity perturbation has a maximum amplitude of 525 nanoGal (nGal). Regarding to the present precision in position measurement, the displacement is too small to be detected. The gravity perturbation should be measurable with superconducting gravimeters, which have a nGal instrumental precision. In experiment 2, the maximum gravity perturbation is about 120 nGal, and in experiment 3, the maximum perturbation is about 33 nGal.

Finally, we investigate the maximum theoretical impact of the Pacific and the African superplumes on the M2 body tide. The superplumes have been modelled as two spherical heterogeneities with a radius of 1000 km in the lower mantle. We find that these superplumes induce a maximum perturbation in gravity of about 370 nGal with a large part corresponding to a mean variation of gravity.

We conclude that we can expect to have a gravity perturbation of body tide with an order of magnitude of about hundred of nGal induced by the biggest mantle heterogeneities of density. This perturbation in gravity should be measurable with superconducting gravimeters if all other contributions in the signal could be extracted with a sufficient precision.

Key words: body tides, elasto-gravity theory, lateral heterogeneity, mantle convection, numerical method, superplumes.

1 INTRODUCTION

At periods longer than 1 hr, the most important part of Earth continuous deformation is induced by luni–solar tides. The attraction of the Sun and the Moon causes global surface motions and variations in the gravity field, which may be observed with geodetic means. The surface displacement can reach about 50 cm and the gravity variations a hundred of μGal.

The body tides have been investigated since the 19th century with the work of Lord Kelvin (Sir William Thomson 1862). Presently, the most accepted earth body tide models deal with an ellipsoidal, rotating Earth, containing a liquid core and an anelastic mantle with hydrostatic pre-stresses (Wahr 1981; Wahr & Bergen 1986; Dehant 1987). The inner structure of the Earth in present tides model is classically based on PREM seismological model (Dziewonski & Anderson 1981).

However, the inner structure of the Earth is more complex than in a Spherical Non-Rotating Elastic Isotropic (SNREI) earth model like PREM. Seismology and fluid dynamic studies show that the mantle presents a heterogeneous structure induced by a thermo-chemical convection (Davaille 1999; Forte & Mitrovica 2001; Gu *et al.* 2001) and departs from hydrostatic equilibrium state. Large lateral heterogeneities have taken place in a million year timescale, as for the two superplumes invoked under the Pacific and South Africa superswells (Courtillot *et al.* 2003). These aspects of the mantle structure are classically not taken into account in the deformation models.

The elasto-gravitational deformations are presently observed with a very good accuracy. The accuracy of superconducting gravimeters and of positioning techniques (GPS, VLBI) has seen a large improvement the last decade. Moreover, different satellites dedicated to gravity measurement have been launched or will be launched, like the GRACE mission in 2002 and GOCE in 2007. One of the purpose of this work is to determine if the present reference body tide model is sufficiently realistic to correct and to understand the coming deformation and gravity data.

Few authors partially investigated the influence of lateral heterogeneities on the Earth tidal deformations. Molodenskiy (1977) was the first to theoretically work on this problem. He investigated a variational approach of the elasto-gravitational equations and their first-order perturbations induced by lateral variations and topographies. Following this way, Wang (1991) computed a model of the Earth solid tides with low degree lateral variations of density and of rheological parameters. Wang (1994) (see also Métivier *et al.* 2005) recalculated also the effect of rotation and ellipticity on the Love numbers. Finally, Dehant *et al.* (1999) studied the influence of the non-hydrostatical ellipticity of internal boundaries on solid tides. These different works globally showed that the effect of low degree lateral variations on solid tides is small but not necessarily negligible regarding to present gravimeter precision. Yet they did not take into account possible deviatoric pre-stresses whose effects on the Earth's body tides are totally unknown.

Taking into account the lateral variations in the calculation is a difficult problem as heterogeneities induce a bias from hydrostatic equilibrium in the Earth. In a companion paper (Métivier *et al.* 2006), we have developed a new earth elasto-gravitational deformation model able to take into account the heterogeneous structure of the mantle. The model has been realized using a spectral element method. The model is solved in two steps: we first determine the solution for a SNREI model with a hydrostatical state of pre-stress, then lateral variations of density, interface topographies, and deviatoric pre-stresses are introduced as perturbations of the SNREI Earth.

The aim of the present article is to evaluate the impact of mantle lateral variations of density on the body tides response of the planet.

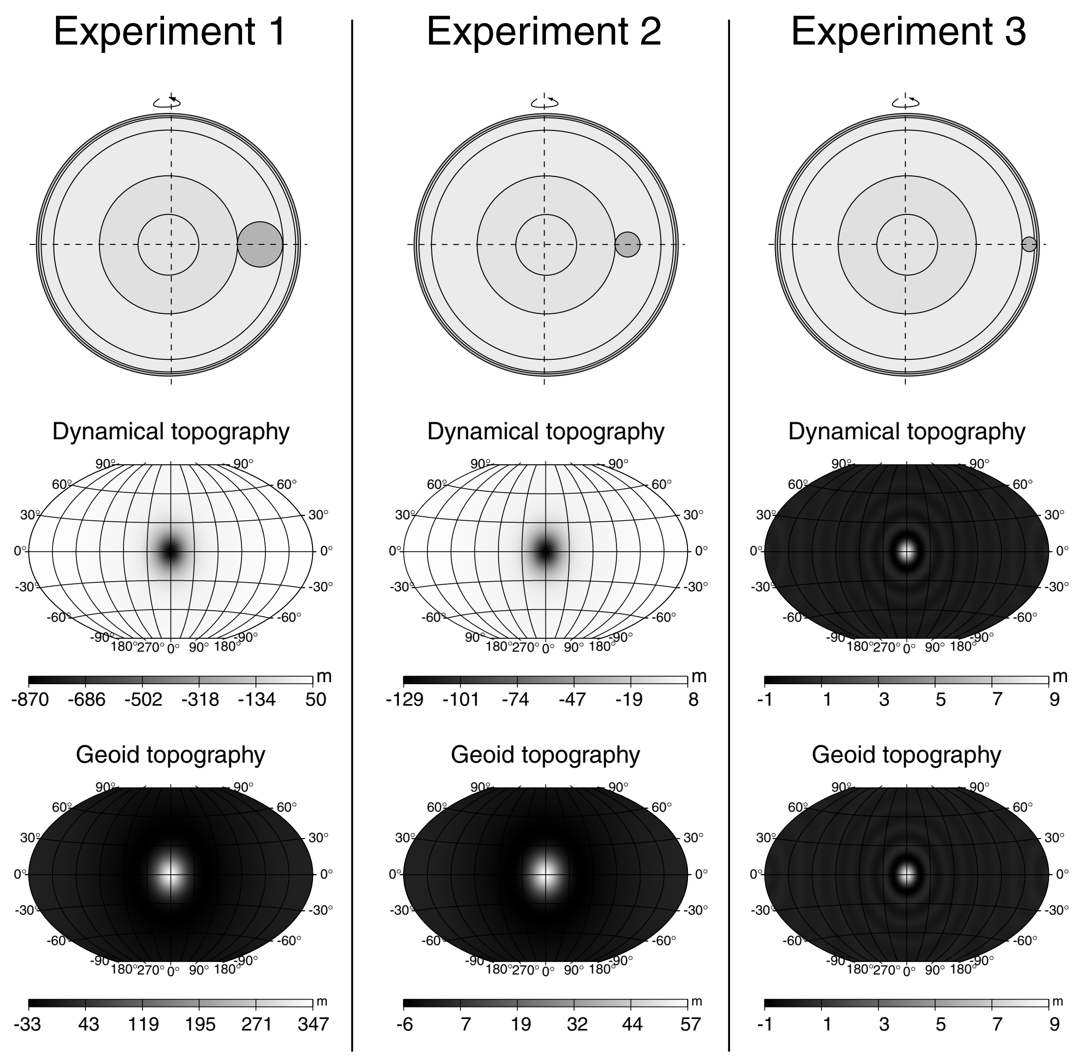

Figure 1. The three models of Earth we discuss here. The figure shows transversal representations of the Earth containing a spherical heterogeneity, and, for each experiment, the corresponding surface dynamical topography and the geoid topography.

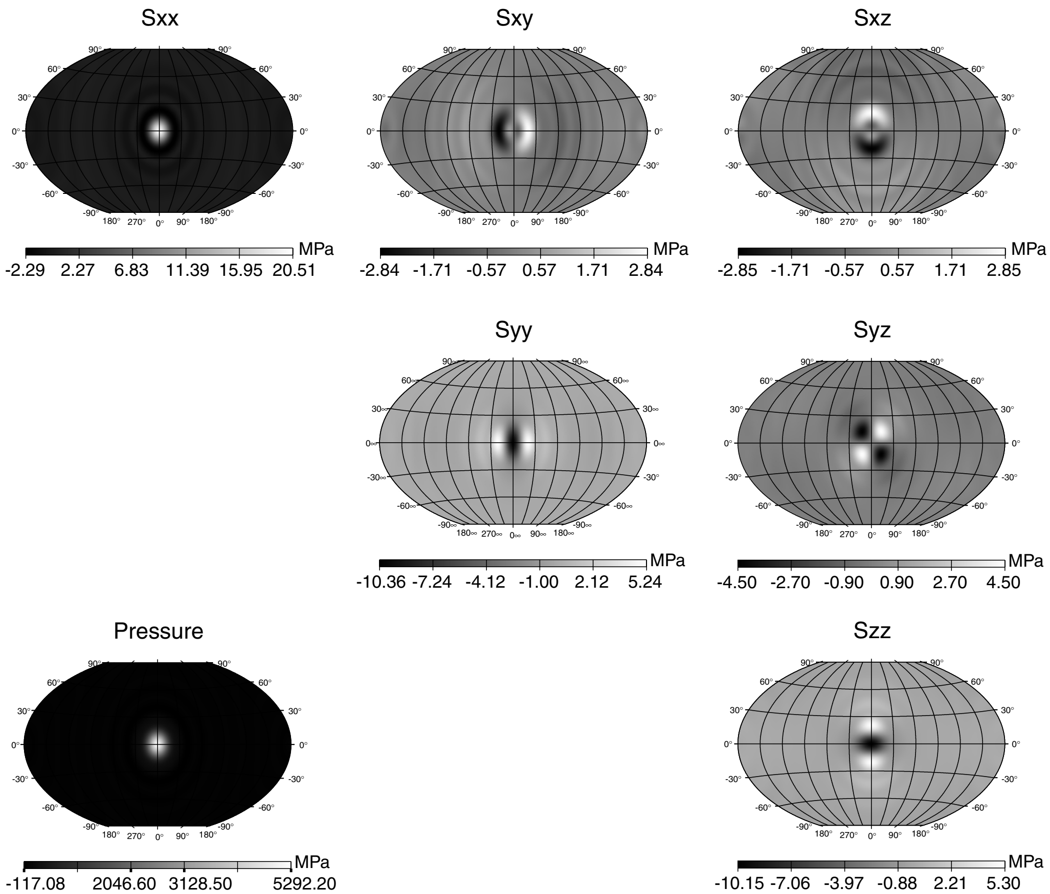

Figure 2. The perturbation of pre-stress tensor in the lower mantle (radius 5043 km) due to the presence of a spherical heterogeneity of density in the mantle (for the experiment 1).

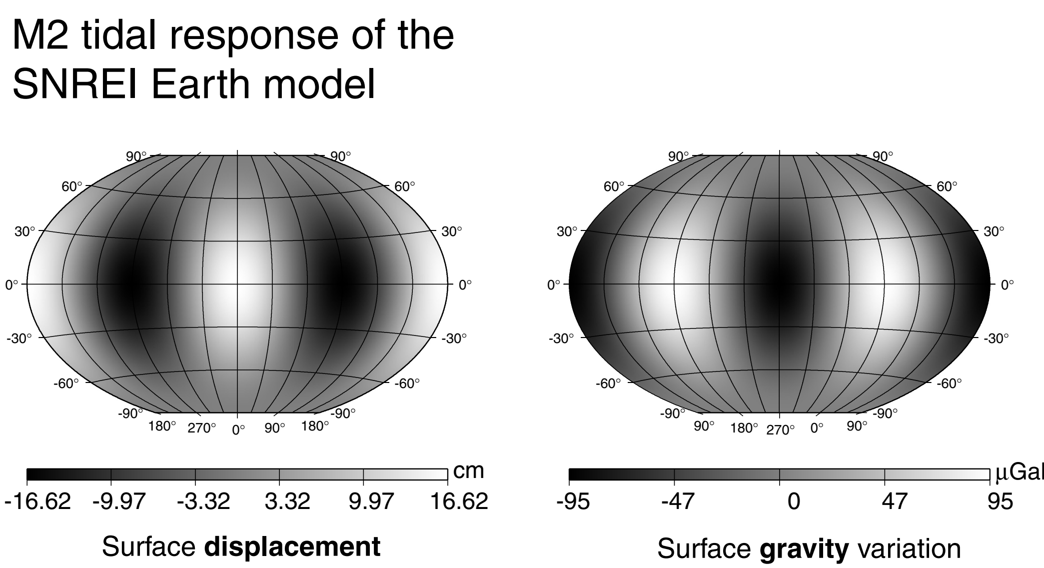

Figure 3. The surface displacement and the surface gravity variation induced by the M2 tide attraction on the SNREI earth model at a time *t*.

In order to understand the relative influence of the different parameters, we investigate tide perturbations induced by simple spherical heterogeneities of density in the mantle. We test three types of heterogeneities of various sizes and positions. Our aim is to provide an idea about tide sensitivity to heterogeneities induced by mantle convection like plumes and superplumes.

The first part of the paper is dedicated to the earth reference model we used. We determine the complex equilibrium state of our planet when it contains a mantle heterogeneity. The presence of lateral heterogeneities in the mantle induces a departure from hydrostatic equilibrium state and dynamical topographies on the interface due to viscous movement in the mantle. In the second part, we study the M2 tide deformation of the planet and determine the perturbation induced by various heterogeneities. Finally, we investigate and discuss the impact of the African and the Pacifican superplumes on body tides.

2 STATIC EQUILIBRIUM STATE OF THE EARTH

We present here, the referential earth model we use in our calculation. A laterally heterogeneous planet presents an equilibrium state more complicated to evaluate than a SNREI earth model. The lateral heterogeneities in the mantle (plumes, superplumes, slabs) are mostly due to a thermo-chemical convection. They induce a departure from hydrostatic equilibrium and a modification of interface shape (the dynamical topography) which have to be known before computing the tidal perturbation.

2.1 The SNREI earth model

Let us define a SNREI earth model composed of fluid and solid layers, in which the physical properties continuously and smoothly vary with radial position. The layers are delimited by spherical surfaces, called internal boundaries, and the global model is bounded by an external surface. For simplicity our model consists of six homogeneous layers: the solid inner core, the liquid core, the D” layer, the lower mantle, the upper mantle and the crust. The density and the elastic parameters of the layers are chosen as average of the PREM model parameters (Dziewonski & Anderson 1981).

2.2 Mantle spherical heterogeneities

Let us define now a new earth model which contains a spherical heterogeneity of density in the mantle rising in the mantle on the

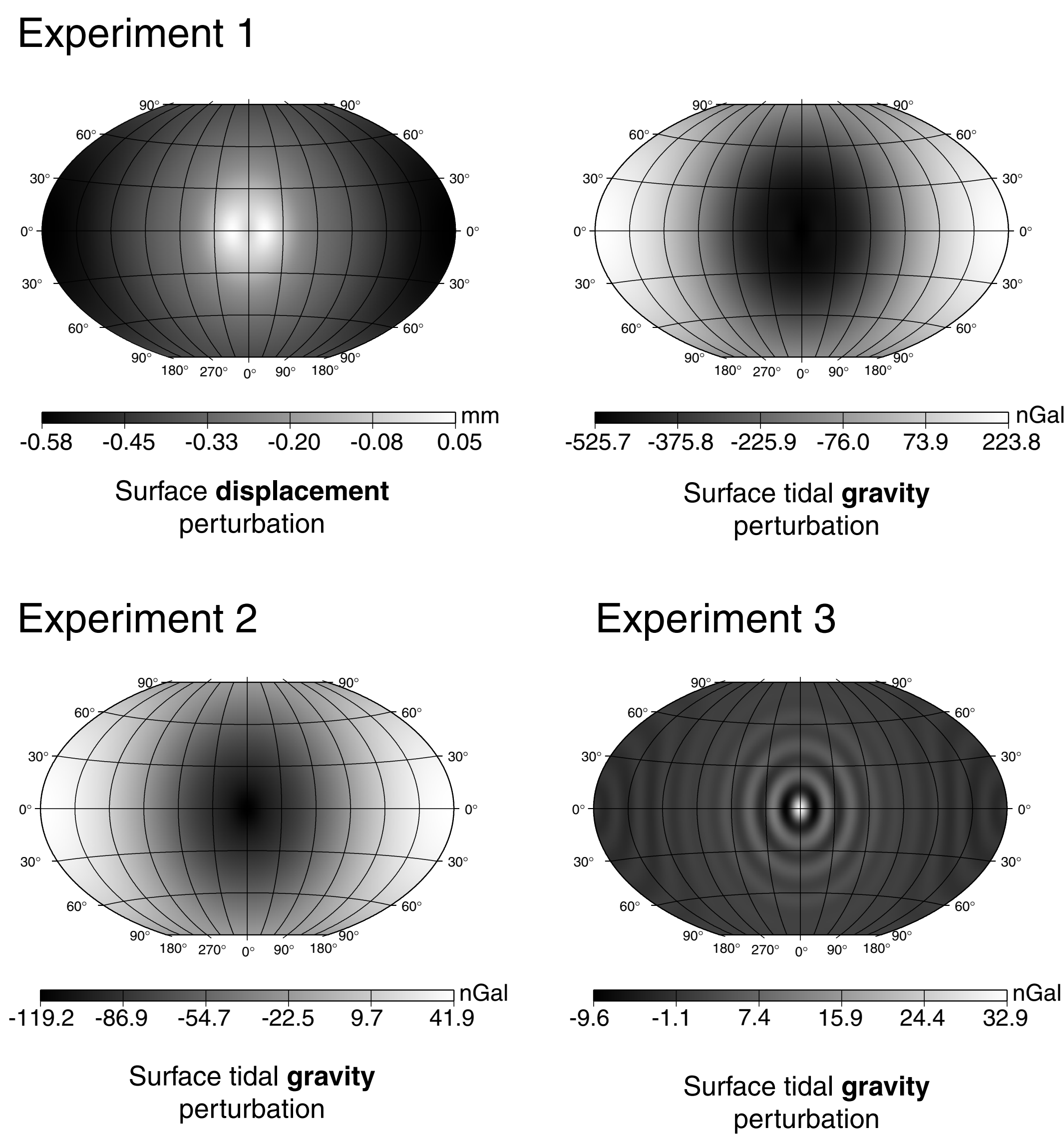

Figure 4. On the top: the perturbations of tidal surface displacement and of tidal surface gravity variation induced by the mantle heterogeneity at a time *t* (experiment 1). On the bottom: the perturbation of tidal surface gravity variation induced by the mantle heterogeneity at a time *t* for experiment 2 and 3.

convection timescale (typically the million years). We assume an elastic lithosphere and a two-layered viscous mantle with a viscosity of 10^{21} and 3. 10^{22} Pa s for the upper and lower mantle, respectively. Knowing this viscosity profile, we can determine the new Earth equilibrium state. The heterogeneities in the mantle are induced by a thermo-chemical convection. They present various shapes and sizes, with a typical density variations of about 1 per cent of the mean density of the Earth. We note particularly that, according to Davaille (1999), the superplumes could have a size as large as the lower mantle thickness. In order to theoretically evaluate the perturbation of the M2 tide induced by the mantle heterogeneities, we present three experiments (Fig. 1): (1) our limit case, with a heterogeneity of 1000 km of radius in the lower mantle; (2) with a heterogeneity of 500 km of radius at the bottom of the lower mantle and (3) with a heterogeneity of 285 km of radius in the upper mantle. We believe that these heterogeneities are representative of mantle plumes and superplumes. In the present study, the shape of the heterogeneities is less important than the mass involved. The density variation has been set to -50 kg m^{-3}. We locate the centre of heterogeneities on the equator because semi diurnal tides are maximum in this latitude. Fig. 1 shows the surface perturbations of topography and of geoid induced by the heterogeneities. The topography is dynamic on a million years timescale, but at tidal timescale, the topography induced by the heterogeneity can be assumed to be static. One can see, in Fig. 1, that the dynamical topography has not the same sign than the geoid topography when the heterogeneity is located in the lower mantle. This is due to the fact that the upper mantle is less viscous than the lower mantle and the lithosphere (elastic). The rising of the heterogeneity in the lower mantle induces in the fluid of the upper mantle tangential movements, which are larger than the local radial motion. Therefore, by coupling, the lithosphere is getting thinner at the top of the heterogeneity and a subsidence can be seen on the surface. The internal boundaries present also topographies, particularly the core–mantle boundary (CMB). When the heterogeneity is located in the lower mantle, the CMB presents a positive topography quite large. In this last case, the geoïd is more affected by the topography on the CMB than on the surface, leading to a geoid topography positive when the surface dynamical topography is negative.

The rising of the heterogeneity in the mantle induces perturbation in the pre-stress equilibrium of the Earth. Supposing that the spherical heterogeneity is evolving in the mantle at the Stoke's velocity, one can determine the new pre-stress tensor of the Earth. For example, we present in Fig. 2 the perturbation of pre-stress tensor components in the mantle (at radius 5043 km) induced by the largest heterogeneity.

In the present paper, we study only density heterogeneities. However, the mantle convection induces also lateral variations in the elastic properties and lateral variations of viscosity. Such aspects of the mantle will be address in the future.

3 THE THEORETICAL M2 BODY TIDE RESPONSE OF THE PLANET

We now discuss here the perturbations induced by the mantle heterogeneities on the M2 body tide of the Earth. The M2 tide is the major tide wave affecting the Earth. It is a semi-diurnal wave tide (with a exact period of 12h27) induced by the Moon attraction. We focused our work on this wave tide in order to evaluate the maximum perturbation induced by mantle heterogeneities on body tides.

3.1 The tidal response of the SNREI earth model

Fig. 3 shows the surface displacement and the variation of gravity potential induced by the M2 tide on our SNREI model, when the Moon is located at longitude zero. The displacement has a maximum of 17 cm and the gravity of almost 100 μGal.

3.2 Impact of lateral heterogeneities

Using the algorithm described in Métivier *et al.* (2006), we computed the tidal perturbation induced by the heterogeneities (see Fig. 1). The method is based on a spectral element method (Komatitsch & Tromp 2002; Chaljub *et al.* 2003; Chaljub & Valette 2004) and is parallelized. We computed the solutions using typically eight processors on the parallel computer server of the Royal Observatory of Belgium. Fig. 4 shows the surface perturbations of displacement and of tidal gravity variation induced by the presence of the largest heterogeneity (experiment 1). The solutions have been computed on the deformed surface of the Earth. This figure shows the maximum perturbations which correspond to the instant when the Moon is just above of the heterogeneity (or at opposite longitude). One can see that displacement perturbation is smaller than 1 mm, and that the gravity perturbation has a maximum amplitude of 525 nanoGal

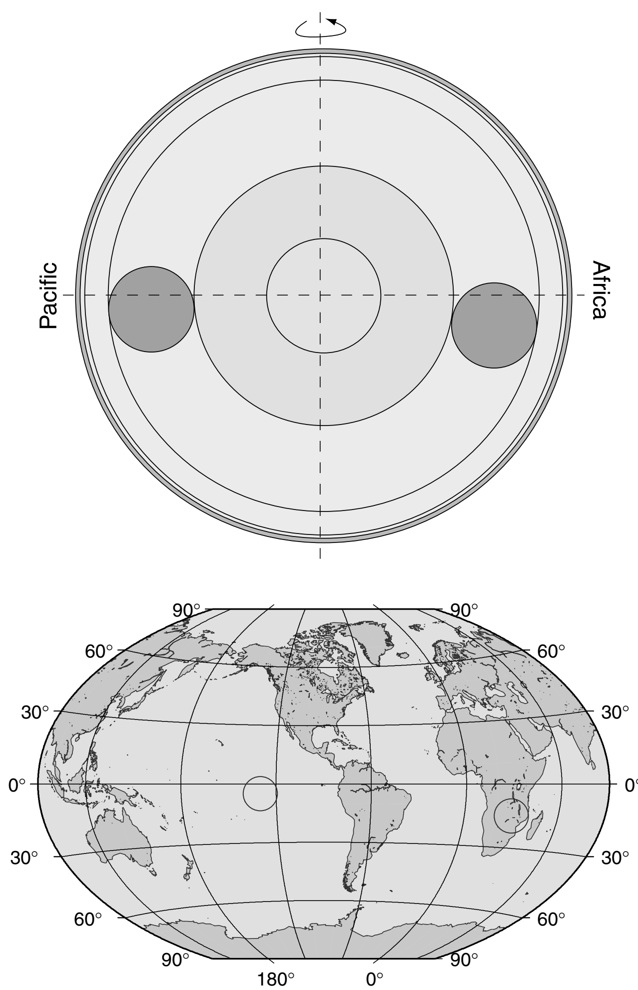

Figure 5. Simple model of the Pacifican and the African superplumes within the Earth. Bottom: the circles show the superplume locations. The radius of the circles corresponds to the radius of the heterogeneities.

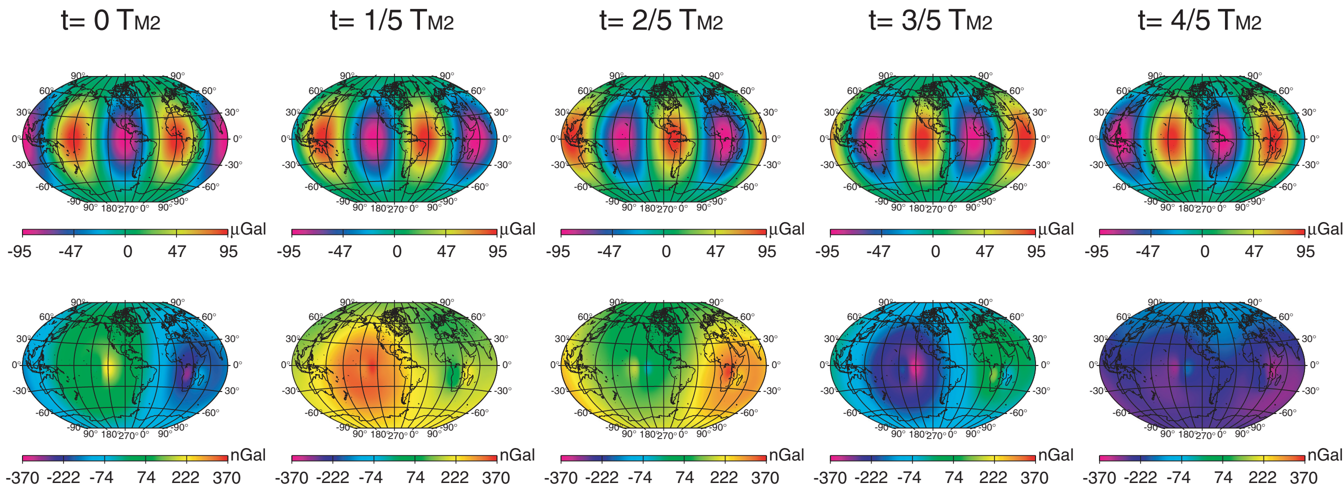

Figure 6. Evolution with time of the gravity variation induced by the M2 tide during one tidal period (TM2 = 12h27), for the earth model shown in Fig. 5. On the top: the tidal gravity variation of the SNREI model, on the bottom: the perturbation of tidal gravity variation induced by the two superplumes.

(nGal). Regarding to the present precision in position measurement, the displacement is too small to be detected. The gravity perturbation should be measurable with superconducting gravimeters which have a nGal instrumental precision. For the experiments 2 and 3, we only present the gravity perturbations since the displacement perturbations are too small to be considered. In the experiment 2, the maximum gravity perturbation is about 120 nGal, and in the experiment 3, the maximum perturbation is about 33 nGal.

4 THE IMPACT OF SUPERPLUMES ON M2 BODY TIDE

Many authors proposed that the mantle convection is dominated by two very large heterogeneities in the lower mantle: the superplumes (see e.g. Davaille 1999; Kerr 1999; Courtillot *et al.* 2003). One would be beneath French Polynesia, the other beneath South Africa. These heterogeneities would be the most important ones in the mantle. We investigate here what would be the maximum perturbation induced by these mantle heterogeneities on M2 tide response of the Earth. Fig. 5 shows the superplumes location in the Earth. We choose to represent the superplumes as two spheres of 1000 km of radius. The solution on surface normal gravity is presented on Fig. 6. The solution presents the perturbation in evolution with time during 1 period of the M2 tide. We see that the maximum perturbation on gravity is about 370 nGal. We note that the solution contains a large degree zero part. Consequently the majority of the time signal corresponds to a mean variation of gravity all over the world (about 200 nGal). This is due to the fact that the heterogeneities are almost at opposite longitude. The semi diurnal tide corresponds to a spherical harmonics of degree 2 and order 2, which means that the tidal attraction is equal at opposite longitude. Therefore, the coupling between the variation of mantle density and of the tidal attraction induces a large degree 0.

5 CONCLUSION

We show that the impact of heterogeneities due to mantle convection on body tide is quite small. The perturbation induced by large-heterogeneities in the mantle is about 1 per cent, in surface tidal displacement and in surface tidal gravity. The displacement perturbation is smaller than 1 mm and consequently cannot be detected with present position measurement techniques. The perturbation in gravity can reach 500 nGal for the largest plausible heterogeneity in the mantle. The order of magnitude is more than 100 times larger than the present superconducting gravimeter precision. We see particularly that superplumes can induce a maximum perturbation in gravity of about 370 nGal. A large part of the signal corresponds to a mean variation of gravity of about 200 ngal.

The superplumes modelled in our experiment are very large. It is probable that superplumes have a smaller dimension, between the heterogeneity of experiment 1 and of experiment 2 in Fig. 1. Regarding to solution in the Fig. 4 we can expect to have a gravity perturbation with an order of magnitude of about 100 nGal induced by these heterogeneities. This perturbation in gravity should be measurable with superconducting gravimeters if all other contributions in the signal could be extracted with a sufficient precision. Thus, the body tides should bring information on the existence or not of heterogeneities like superplumes in the Earth mantle.

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